

APPLICATION OF SEISMIC METHODS TO MINERAL EXPLORATION

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Abstract

Plots of compressional (V_p) and shear (V_s) wave velocity vs. density for rocks at elevated confining pressures show that velocities tend to increase with density along the well known Nafe-Drake curves for silicate rocks. Because of their high densities, however, many ores fall far to the right of the Nafe-Drake curves and display higher impedances than their common hosts, suggesting that it should be possible to detect and prospect for ores using high-resolution reflection techniques if the deposits meet the size, thickness, and presentation constraints required for reflection or diffraction. Experiments conducted by the Geological Survey of Canada, universities, and industry in hardrock mining camps across Canada over the past decade show that 2-D surveys are well suited to the determination of structure and the detection of orebodies, while 3-D surveys may be used for detection and delineation, and vertical seismic profiling (VSP) for delineation. Due to the small size of most deposits, the structural complexity of hard rock terranes and their low signal-to-noise ratios, the best results are obtained from carefully designed surveys using high frequency sources and customized processing sequences designed to identify both reflections and diffractors.

2-D and 3-D surveys have successfully detected and imaged large massive sulphide deposits such as the magmatic and volcanic massive sulphide (VMS) deposits in Sudbury and Bathurst and should also be useful for the detection of massive sedimentary exhalative (SEDEX) and iron oxide copper gold (IOCG) deposits. Other types of deposits are more likely to be detected indirectly: lode gold and porphyry deposits by reflections from alteration haloes, unconformity Uranium deposits by haloes and basement offsets, and Mississippi Valley-type (MVT) deposits by white spots in otherwise reflective carbonates. Similarly, the high impedances between kimberlites and their hosts allow pipes to be delineated using VSP techniques.

Résumé

Des tracés des vitesses des ondes de compression (V_p) et de cisaillement (V_s) en fonction de la densité des roches soumises à des pressions de confinement élevées montrent que ces vitesses ont tendance à augmenter en fonction de la densité en suivant les courbes bien connues de Nafe-Drake pour les roches silicatées. Cependant, en raison de leur densité élevée, un grand nombre de minerais génèrent des courbes qui se situent loin à droite de celles de Nafe-Drake et présentent des impédances plus élevées que les roches hôtes dans lesquelles on les trouve couramment, ce qui suggère qu'il pourrait être possible de les détecter à l'aide de méthodes de prospection par sismique-réflexion haute résolution si les gîtes sont conformes aux contraintes de taille, d'épaisseur et de présentation imposées par la sismique-réflexion ou la sismique-diffraction. Des expériences menées par la Commission géologique du Canada, des universités et l'industrie dans des camps miniers en roche dure d'un bout à l'autre du Canada au cours de la dernière décennie montrent que les levés 2D conviennent bien pour la détection et la détermination de la structure des corps minéralisés alors que les levés 3D peuvent être utilisés pour leur détection et leur délimitation et le profilage sismique vertical (PSV) pour leur délimitation. En raison de la petite taille de la plupart des gîtes, de la complexité structurale des terrains de roche dure et de leurs faibles rapports signal sur bruit, les meilleurs résultats sont obtenus dans le cadre de levés soigneusement conçus exploitant des sources haute fréquence et des séquences de traitement adaptées spécifiquement à l'identification des réflexions et des diffractions.

Des levés 2D et 3D ont permis de détecter avec succès et de produire des représentations de grands gîtes de sulfures massifs, comme les gisements magmatiques et les gisements de sulfures massifs volcanogènes à Sudbury et à Bathurst, et devraient également être utiles pour la détection de gîtes sedex et de gîtes d'oxydes de Fer-Cu-Au massifs. Il est plus vraisemblable que d'autres types de gîtes soient détectés de manière indirecte : les gîtes d'or primaires et les gîtes porphyriques d'après les réflexions de leurs auréoles d'altération, les gîtes d'uranium associés à des discordance d'après les auréoles et les décalages du socle et les gîtes de type Mississippi-Valley d'après des taches blanches dans des roches carbonatées par ailleurs réfléchissantes. De même, les impédances élevées entre les kimberlites et leurs roches hôtes permettent la délimitation des cheminées par des méthodes de PSV.

Overview

The mining industry has traditionally used geologic field mapping, electromagnetic and potential field techniques, and drilling to explore for new mineral deposits, but with new discoveries of large near-surface deposits becoming increasingly rare and the known reserves of most economic minerals in decline, it is clear that new deep exploration techniques are required to meet the future needs of industry and society. With gravity and magnetic methods unable to resolve targets beyond about 500 m, high-resolution seismic reflection techniques similar to those used by the petroleum industry, but

modified for the hardrock environment, show the greatest potential for extending exploration to depths of 3 km, the current maximum depth of mining.

Reflectivity and Resolution: Basic Factors

Two basic factors govern whether or not a potential reflector can be detected and imaged by seismic reflection techniques: the difference in acoustic impedance between the deposit or horizon and its surroundings, and its geometry. The acoustic impedances (velocity-density products) of common rock types and ores are well known from laboratory

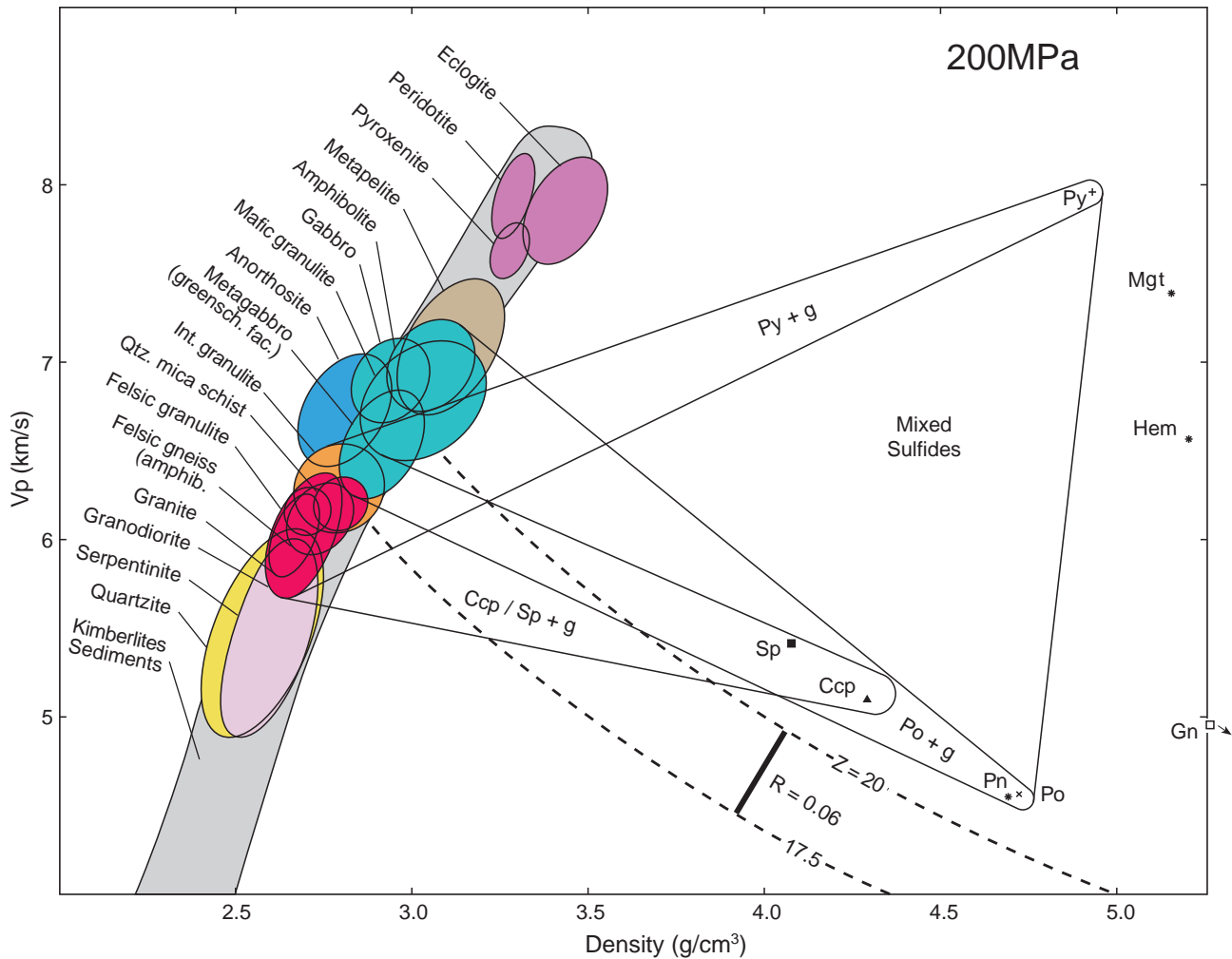


FIGURE 1. Lines of constant acoustic impedance (Z) superimposed on velocity-density fields and Nafe-Drake curve (grey) for common rocks at a standard confining pressure of 200 MPa (modified from Salisbury et al., 2003). Also shown are values for pyrite (Py), pentlandite (Pn), pyrrhotite (Po), chalcocopyrite (Ccp), sphalerite (Sp), hematite (Hem), magnetite (Mgt), and fields for host rock-ore mixtures. A reflection coefficient (R) of 0.06 is sufficient to give a strong reflection. Galena (Gn, off scale) has a velocity of 3.7 km/s and a density of 7.5 g/cm².

and logging measurements (eg. Christensen, 1982; Salisbury and Iulucci, 1999; Ji et al., 2002) and are summarized in Figure 1. As a rule of thumb, an impedance (Z) difference of 2.5×10^5 g/cm²s between two rock types having velocities v_1 and v_2 and densities ρ_1 and ρ_2 will give a reflection coefficient,

$$R = \frac{v_2\rho_2 - v_1\rho_1}{v_2\rho_2 + v_1\rho_1} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

of 0.06, which is sufficient to give a strong reflection if the geometry is appropriate (Salisbury et al., 1996, 2003). Thus contacts between mafic and felsic igneous rocks ($Z \sim 20$ and 17.5, respectively) or between most sulphide ores ($Z \geq 22$) and most country rocks can be strongly reflective, whereas contacts between similar rocks, such as metagabbro and anorthosite, are not.

The second factor that governs whether or not a deposit can be resolved is its geometry, especially its size and depth of burial. The minimum thickness, t , that can be uniquely determined for a tabular deposit can be estimated from its tuning thickness,

$$t = v/(4f)$$

where v and f are the average velocity in the deposit and the dominant acoustic frequency used in surveying, respectively. This thickness, also called the Rayleigh limit or quarter wavelength criterion (Widess, 1973), is the thickness for which seismic waves reflecting off the top and bottom surfaces of the deposit constructively interfere. For thicker deposits, the two reflections separate in time, allowing the thickness to be uniquely determined. Thinner deposits can be detected as well, but the two reflection surfaces cannot be resolved and the combined reflection amplitude decreases to that of a single reflector.

Similarly, the smallest diameter deposit that can be resolved at any given depth, z , as a surface rather than a diffractor, is defined by the width of the first Fresnel zone,

$$d_F = (2zv/f)^{1/2}$$

where v is now the formation velocity. As in optics, the first Fresnel zone is the area of a planar reflector from which the reflected energy in the first quarter wavelength of a spherical wave front constructively interferes. Modeling results show that deposits as small as one wavelength across can still be detected as diffractors under ideal conditions but that smaller deposits will be undetectable due to attenuation (Berryhill,

1977). Thus in principle, a body which is 15 m thick by 60 m across could be detected as a point source at a depth of 1 km, assuming a formation velocity of 6 km/s and a dominant frequency of 100 Hz, and a body ≥ 350 m across could be resolved as a reflector. Deeper deposits have to be larger to be imaged, which is consistent with the economics of deep mining.

Given the resolution limits discussed above, seismic reflection can potentially be used for mineral exploration in three ways: 1) to identify and trace prospective structures and horizons at depth, such as the petroleum industry does today, 2) to detect and image new deposits directly, and 3) to delineate known deposits. Several different techniques have been developed by the petroleum industry over the past 70 years for shooting, acquiring, and processing seismic data, including 2-D, 3-D, and Vertical Seismic Profiling (VSP). These techniques will be briefly described below, along with the modifications that have been used to make them work in hardrock terranes. Refraction techniques will not be described because they currently lack the resolution needed for exploration.

Seismic Reflection Methods

2-D

If a sound wave from a seismic source at the surface reflects off a buried horizontal reflector, as in Figure 2a, the angle of incidence α will equal the angle of reflection and the signal will be received at a point that is equidistant from the common midpoint (CMP) at a time controlled by the velocity of sound and the total path length through the upper layer. Rays entering deeper layers will bend according to Snell's law at each horizon where the velocity changes. Thus in Figure 2a:

$$\frac{\sin \alpha_1}{\sin \beta_2} = \frac{v_1}{v_2}$$

where α_1 and β_2 are the angles of reflection and refraction at the interface and v_1 and v_2 are the acoustic velocities above and below.

While geophones are generally used as the receivers, a variety of sound sources can be used for seismic surveys on land, including impulsive sources such as Betsy guns and weight drop systems, dynamite in shallow boreholes, airguns in water-filled pits or fluid-filled pans attached to vehicles, and vibroseis trucks, which can be programmed to deliver a sweep-frequency waveform into the ground that rises (for example) from 10 to 100 Hz over a period of 12 seconds. As can be seen in Figure 2b, the sources and receivers are laid out at regular surveyed intervals along the seismic line, and each shot is monitored by a linear array of receivers since there is no way to predict *a priori* where the signal will intercept the surface if the reflectors are dipping or to predict the effects of refraction on deeper ray paths. The line is then shot by moving the shot point and the array forward in sync as the data is recorded until the line is completed. To improve the signal-to-noise ratio of the field records, multiple shots or multiple sweeps are usually conducted at each source point, a group of geophones is set out at each receiver position, and the recordings are summed. Depending on the length of the line, the spacing between receiver positions in the array, and the number of geophones in each group, it is not uncommon

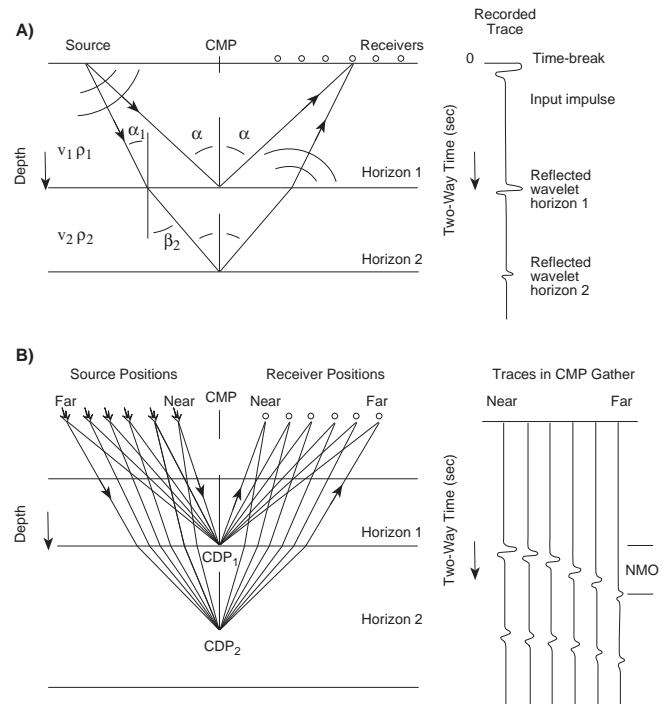


FIGURE 2. (A) Source-receiver geometry and recorded signal for simple 2-D reflection from buried horizontal reflectors (modified from Nelson, 1949). CMP is the common midpoint. α , β , v , and ρ are angle of incidence, angle of reflection, velocity, and density, respectively in layers 1 and 2. (B) Far- and near-source receiver positions for a typical CMP gather. NMO = normal moveout.

to have hundreds of geophone channels active at any one time.

After shooting, the geophone data is multiplexed and transmitted back to a central field computer where it is pre-processed and recorded for subsequent digital processing to remove noise and present the data as a geometrically correct plot of reflection amplitude versus time (depth) and distance along the seismic line. As can be seen in Table 1, conventional preprocessing and processing involves several steps (Yilmaz, 1987), but these are commonly varied to suit the problem being addressed. Preprocessing in the field involves demultiplexing and reformatting the data from the receiver array, environmental noise has to be edited out and amplitude adjustments, such as automatic gain control (AGC), need to be applied to correct for geometric spreading. In addition, the geometry of the survey (latitude, longitude, and elevation of shot and receiver positions) is established at this time and initial static corrections (time shifts) are applied to the data based on the geometry.

After preprocessing, the data is simplified by deconvolving all but the initial wavelet of the source signal from the received signal and all of the signals received from each common depth or midpoint (CMP) along the line are gathered as in Figure 2b. Velocities are then estimated as a function of time (velocity analysis) for selected CMP gathers by determining the velocity that best flattens the gather at each depth. This allows the static corrections to be improved by incorporating the effects of shallow low-velocity zones caused by weathering, which in turn, allows for reiterative improvement of the velocity analyses themselves. Once this is done, the signals are further improved by stacking the flattened gathers

TABLE 1. Conventional Processing Sequence (after Yilmaz, 1987).

1. Preprocessing
Demultiplex
Reformat
Edit
Geometric spreading correction
Set up field geometry
Application of field statics
2. Deconvolution
3. CMP sorting
4. Velocity analysis
5. Residual statics correction
6. Velocity re-analysis
7. NMO correction
Muting
Stacking
8. Time-variant band-pass filtering
8. Migration

(i.e. applying the normal moveout, or NMO correction) for each reflection point (bin) to improve the signal-to-noise ratio, the degree of improvement increasing with the square root of the number (fold) of shot-receiver pairs that are stacked for each CMP. Time-variant band pass filters are then applied to normalize the signal for attenuation effects and to examine the data at selected frequencies, and finally, the data is migrated to restore the geometry and the results adjusted for strike and crooked line effects. While the final objective is, of course, to present the reflection data as a function of depth, it should be emphasized that all of the processing steps outlined above are conducted in the time domain.

3-D

Two-dimensional surveys can be used for reconnaissance and to resolve simple structures at depth, but complicated structures causing out-of-plane reflections (sideswipe) can only be imaged using 3-D reflection techniques in which a 3-D volume of crust is ensounded and monitored using a planar, rather than an a linear, array of shots and receivers. In practice, this is accomplished by laying out thousands of geophones along parallel lines of receiver groups and then shooting to the entire array from each shot point along a series of orthogonal shot lines as in Figure 3. Although complicated by the fact that a typical 3-D survey contains orders of magnitude more data to process, the actual processing steps are fairly similar to those for 2-D surveys, although they use specialized 3-D migration algorithms. The end result, however, is a data cube that can be sliced to produce synthetic 2-D profiles in any arbitrary direction through the data, horizontal slices at arbitrary depths (time slices), horizon slices showing reflectivity variations in map plan for picked marker horizons, and 3-D tomographic images that can be viewed from any perspective.

Vertical Seismic Profiling (VSP), Borehole Seismic

2-D and 3-D seismic techniques are effective for mapping most structures at depth but less so for mapping steeply dipping structures ($>60^\circ$) or to determine interval velocities or gradients where reflections are absent. These problems can be addressed, however, using borehole seismic techniques in which a seismometer is lowered to the bottom of a drillhole and then raised in stages as shots are fired to the seismometer and nearby reflectors from the surface (Fig. 4a). If the shot position is known and the borehole geometry has been

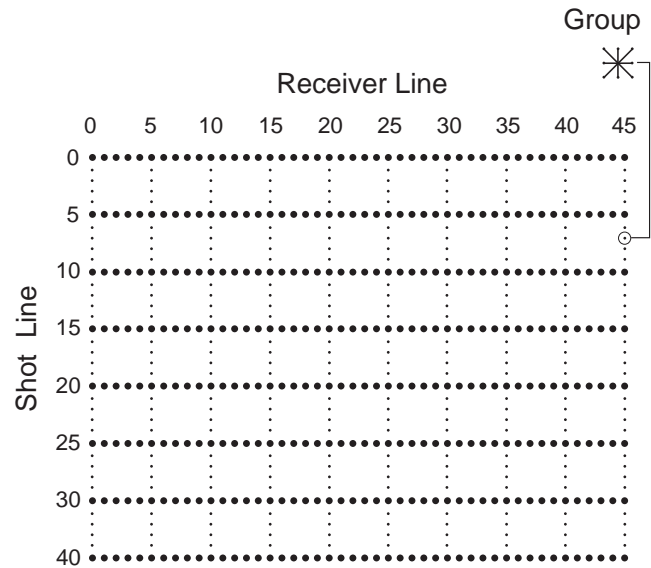


FIGURE 3. Shot (bold) and receiver (faint) positions for a typical 3-D reflection survey. Each receiver position is occupied by a group of geophones to increase signal-to-noise ratio. Fold increases inward.

determined from directional surveys, interval velocities can be calculated from the shot-receiver distances and direct arrival transit times (Fig. 4b), and the geometry of reflectors in the area can be determined using the common depth point (CDP) transform method (Dillon and Thomson, 1984). Directional ambiguities to reflectors can be removed through the use of three-component seismometers and more complex three-dimensional structures can be resolved through the use of linear and spatial arrays of shot points.

Seismic Exploration for Minerals – Special Considerations

While the seismic reflection methods used for petroleum and minerals exploration are similar, minerals exploration poses special problems that must be taken into account.

Most economic mineral deposits are found in hardrock, rather than sedimentary environments. Since the impedance contrasts and reflection coefficients between most common igneous and metamorphic rocks are smaller than those between sedimentary rocks ($R \sim 0.1$ vs. 0.3), the signal-to-noise (S/N) ratio in minerals surveys will be low, making it more difficult to image structures in the country rock. Particular care must thus be taken during acquisition and processing to maximize the S/N ratio. This is typically done by using explosives in shallow boreholes filled with water or tamped with sand to ensure good source coupling to bedrock, by using cemented or clamped geophones whenever possible, by careful testing of different sources before conducting the survey itself, and by maximizing the fold (Eaton et al., 2003).

Velocities in igneous and metamorphic rocks are typically higher than sediments. Since wavelength varies with velocity for any given frequency, higher frequencies are required in hardrocks than sediments to achieve comparable resolution, which is another reason for using explosives.

Structures in hardrock terranes are often complex and steeply dipping, requiring high resolution (>100 Hz), high fold surveys to be resolved. Since reflections from dipping reflectors tend to arrive at the surface at unexpected loca-

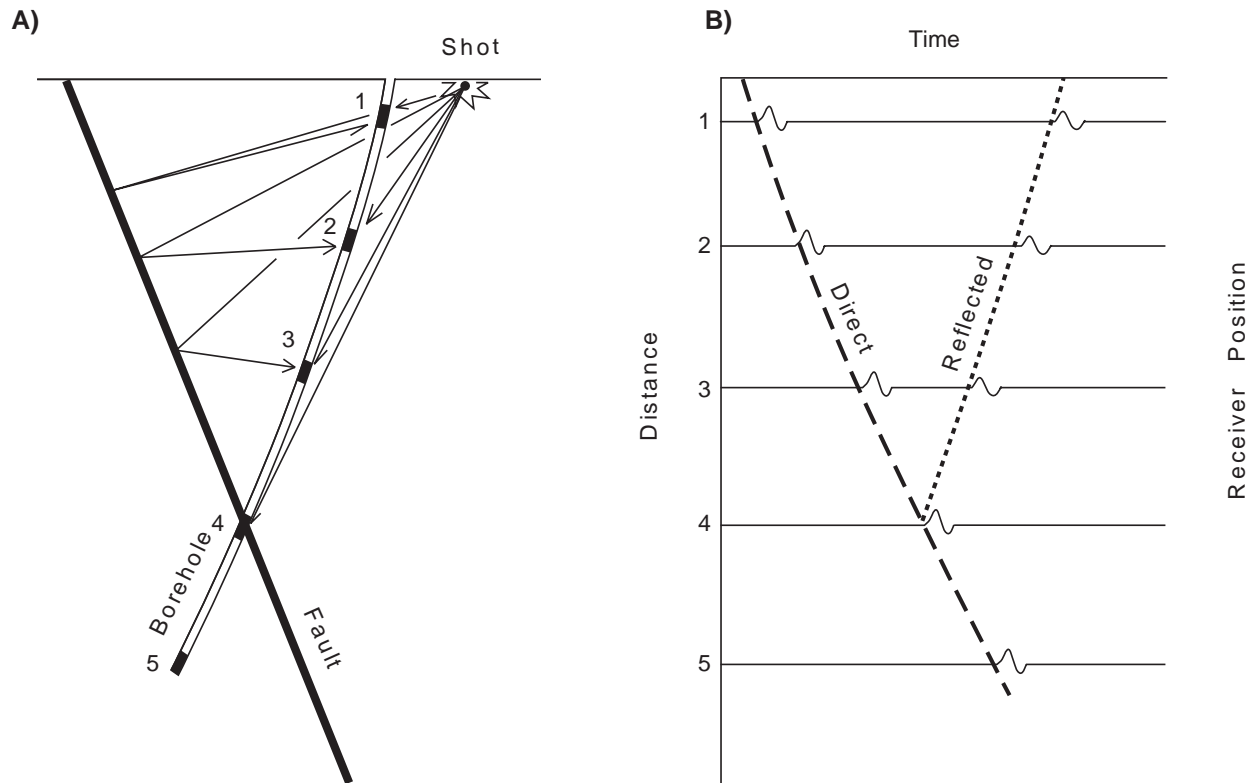


FIGURE 4. (A) Shot and receiver positions in a typical borehole or VSP seismic survey. (B) Distance-time plot showing transit times for direct and reflected arrivals from steeply dipping reflector.

tions, it is often necessary to model surveys in such terranes in advance in order to determine the optimum locations for receivers and to interpret the data.

Since even rich ore deposits are often fairly small (<1 km across), they commonly appear as diffractions rather than reflections on seismic reflection profiles. Processing of reflection data from mineral surveys thus often involves two processing streams, one to image structures such as folds or faults in country rock and one to locate, enhance, and trace diffractions to their sources using unmigrated data (Table 2). Prestack migration, a sophisticated processing technique in which the data is migrated without any prior stacking, is used in this second stream because conventional processing tends to treat small targets as noise. While prestack migration is a powerful and rewarding processing tool, it must be used with caution because it is both challenging and expensive.

Finally, since some types of ores only have small impedance contrasts with many common host rocks, it is often advisable to conduct laboratory measurements of the velocities and densities of the ores and host rocks in a potential survey area to determine whether reflections are even possible and the survey worth conducting.

While seismic reflection techniques can be used to explore for ore deposits at much greater depths than any other remote geophysical technique, they are expensive, with high-resolution 3-D surveys costing ~\$50K /km² for acquisition and processing (Adam et al., 2003), 2-D surveys ~\$6K /km, and a typical VSP survey to a depth of 500 m in a pre-existing borehole, ~\$30K total. Since 2-D surveys are best suited to structural reconnaissance, 3-D surveys to discovery and delineation, and VSP surveys to delineation, and

the costs are significantly different, it is important to match the method to the intent of the survey and the type of deposit sought. As outlined below, this is best accomplished from knowledge of the geology and acoustic properties of both the country rocks and the deposits themselves.

Applications by Deposit Type

Diamonds

Although diamonds occasionally occur in placer deposits, their primary occurrence, both in Canada and worldwide, is

TABLE 2. Mineral Survey Processing Sequence (after Adam et al., 2003).

1. Preprocessing
Demultiplex
Set up field geometry
Edit
True amplitude recovery
2. Deconvolution
3. Band-pass filtering
4. Gain control
5. First break mute
6. Refraction statics corrections
7. Residual statics corrections
8a. Unmigrated Stack
Dip moveout (DMO) corrections
Velocity analysis
NMO correction
Stacking
Band-pass filter
8b. Migrated Stack
Prestack migration
Velocity analysis
Scaling
Band-pass filter

in kimberlite pipes, craters, and dykes in Archean terranes (Kjarsgaard, 1995). The pipes, which generally occur in swarms, are small (a few hundred metres across), carrot-shaped deposits with steep sides (75–85°). Feeder dykes, sills and blows are common at depth and relatively large crater facies deposits with shallow-dipping (0–35°) bedrock contacts may be present if erosion is shallow. Since they were emplaced as diatremes, usually during the Phanerozoic, the pipes often cut both PreCambrian basement and later sedimentary cover rocks.

Because diamonds are only trace constituents in even the richest kimberlites, their presence or absence cannot be ascertained using seismic methods. As can be seen in Figure 1, however, kimberlites often have much lower impedances than basement igneous and metamorphic rocks and most sedimentary rocks as well, which suggests that kimberlite contacts with the country rocks should make strong reflectors. This makes seismic methods potentially very useful for the delineation of kimberlite structures and for estimating their volumes, both important factors in diamond mining. The walls of pipes and dykes are usually steeply dipping, so they will be difficult to image, but shallow-dipping sill and crater facies contacts will be easily detectable using 2- and 3-D techniques. This suggests that it would be inappropriate to use seismic reflection to explore for pipes but that borehole techniques can be used to delineate their walls, as in the recent Victor kimberlite experiment (Bellefleur et al., 2005). 2- and 3-D methods can be used, however, to explore for kimberlite sills, to look for reflection terminations where sediments are cut by pipes, to delineate crater floors, and to look for whispering modes that are diagnostic of pipes (Urosevic and Evans, 1998, 2000). Alternatively, marine reflection techniques could be used to identify and map the tops of kimberlites in lake floors on the basis of their low reflectivity compared to shield rocks.

Lode-Gold Deposits

Most gold in Canada is mined from bedrock sources and those bedrock deposits that are mined largely, or exclusively for their gold content, are termed lode-gold deposits. While most occur in greenstone belts containing volcanic and sedimentary rocks of low to intermediate metamorphic grade, and there are many different kinds of these deposits, most belong to one of four groups, depending on differences in structure, composition, and origin:

- Epithermal gold deposits, in which gold and silver are found in fault-controlled veins and breccia in shallow hydrothermal deposits associated with silicic to intermediate volcanics and intrusives. Since the noble metals are only minor constituents of these deposits, their presence cannot be determined seismically. The most distinctive features of these deposits are the breccias that host the ores and the alteration haloes that surround them. Since the breccias and haloes will have low impedances due to their high chlorite, sericite, and clay contents, these deposits should produce strong reflections against their hosts, if contacts are sharp and not gradational. These structures would be detectable as diffractors using VSP and high-resolution, wide-angle 2- and 3-D seismic reflection techniques.

- Quartz-carbonate vein gold deposits, in which gold occurs in veins in obduction or collision-related faults and shear zones in deformed clastic sedimentary terranes or deformed volcanic/plutonic terranes containing arc and ophiolite assemblages. Vein deposits in clastic terranes lack aureoles, making them unattractive targets for direct detection and imaging. Seismic reflection can be used, however, to map promising structures such as fold axes or to track known deposits across fault offsets (Coflin et al., 1995). Since vein deposits in volcanic/plutonic terranes commonly occur in wide, schistose shear zones with carbonate alteration haloes and the country rocks display a wide range of impedances, the use of seismic reflection would be limited to mapping local and regional structure in support of conventional exploration.
- Iron-formation-hosted stratabound gold deposits, in which gold is found in intimate association with pyrrhotite or pyrite in strongly deformed iron formation. Whether the sulfides are conformable with the iron formation or concentrated in secondary fold axes, both iron formation and pyrite have high impedances, making these deposits excellent targets for seismic exploration and delineation.
- Disseminated and replacement gold deposits, in which gold is disseminated with other sulphides in structurally stratabound host-rock units composed of schists or carbonates. With the possible exception of the ores hosted by schists, which may have low impedances, these deposits have no distinguishing acoustic or structural characteristics to make them amenable to seismic prospecting.

Magmatic Ni-Cu-PGE Deposits

Magmatic sulphides, which have segregated from large intrusions or flows of mafic or ultramafic magma, are the principle source of Ni, Cu, and PGE minerals in Canada and the world. The sulphides are usually found as massive deposits that were concentrated by gravitational settling near the base of their magmatic hosts. In the case of the larger magma bodies, such as the Bushveld Complex and the Sudbury Complex (an impact structure) and intrusions associated with rifting and flood basalts, the magmas themselves have been differentiated, while the smaller komatiitic hosts remained undifferentiated.

As can be seen in Figure 1, seismic reflection techniques are well suited to mapping both the internal stratigraphy and structure of layered or stratified igneous complexes and their contacts with the country rock because ultramafics, mafics, and late differentiates all have sufficiently large impedance differences to reflect against each other and the ultramafics or mafics at the base will reflect against most country rocks, as will komatiites. This is clearly born out in the Bushveld Igneous Complex where 3-D surveys show cumulate stratigraphy and individual sulphide/platinoid and chromitite ore horizons with such clarity that they are routinely used for mine planning (Fig. 5; Duweke et al., 2002). Similarly, 2-D surveys conducted as part of an extended study of the Sudbury Basin (Figs. 6, 7) clearly show the granophyre/norite and footwall contacts as well as the deep structure of

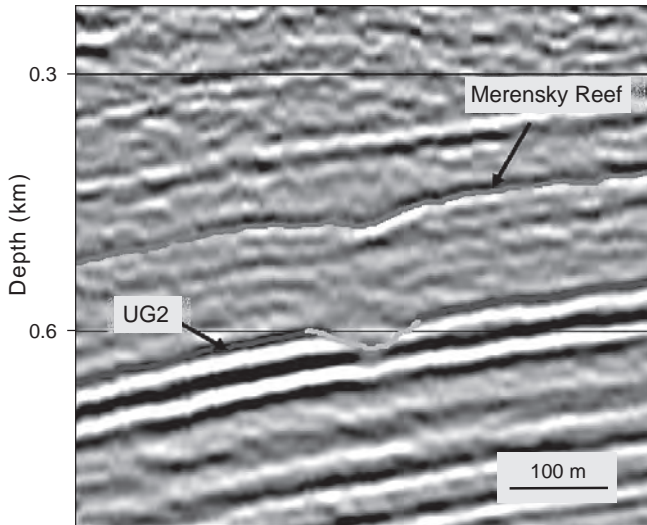


Figure 5. Section from 3-D survey in the Bushveld Complex, South Africa, showing sulphide/platinoid-bearing Merensky Reef and UG2 chromitite layer in gabbroic cumulates. Figure modified from Duweke et al., 2002.

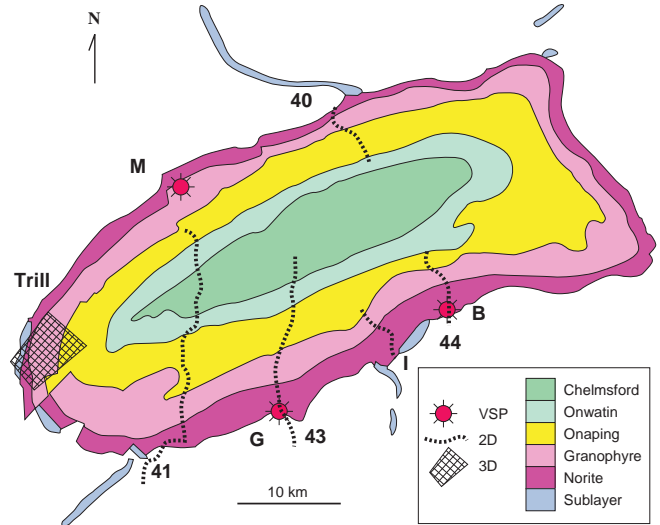


Figure 6. Locations of 2-D (lines 1, 40, 41, 43 and 44), 3-D (Trillabelle (Trill) deposit) and vertical seismic profiling (VSP) (McCreedy (M), Gertrude (G), and Bleazard (B) deposits) surveys conducted by the Geological Survey of Canada, industry, and Lithoprobe in the Sudbury Basin.

the basin (Milkereit et al., 1992) and horizon slices through a 3-D cube at the Trillabelle deposit in Sudbury (Fig. 8) show clear images of the footwall (Milkereit et al., 1997). Since massive sulphides have considerably lower impedances than ultramafics, and markedly higher impedances than the sub-layer norite or the country rock in Sudbury, large sulphide bodies imbedded along the footwall can be directly detected from their diffraction patterns in both 2-D and 3-D surveys (Figs. 8, 9; Milkereit et al., 1996). By inference, it should be possible to use 3-D techniques to explore for Ni-Cu-PGE

deposits at the base or around the margins of any large mafic to ultramafic complex that picked up enough sulphur to precipitate sulphides.

Volcanic Massive Sulphide Deposits

Volcanic massive sulphide (VMS) deposits are squat to tabular, generally concordant deposits of massive sulphides formed by seafloor hydrothermal activity in oceanic, arc or back-arc environments. The deposits, which are typically found in sedimented grabens in mafic and felsic volcanics,

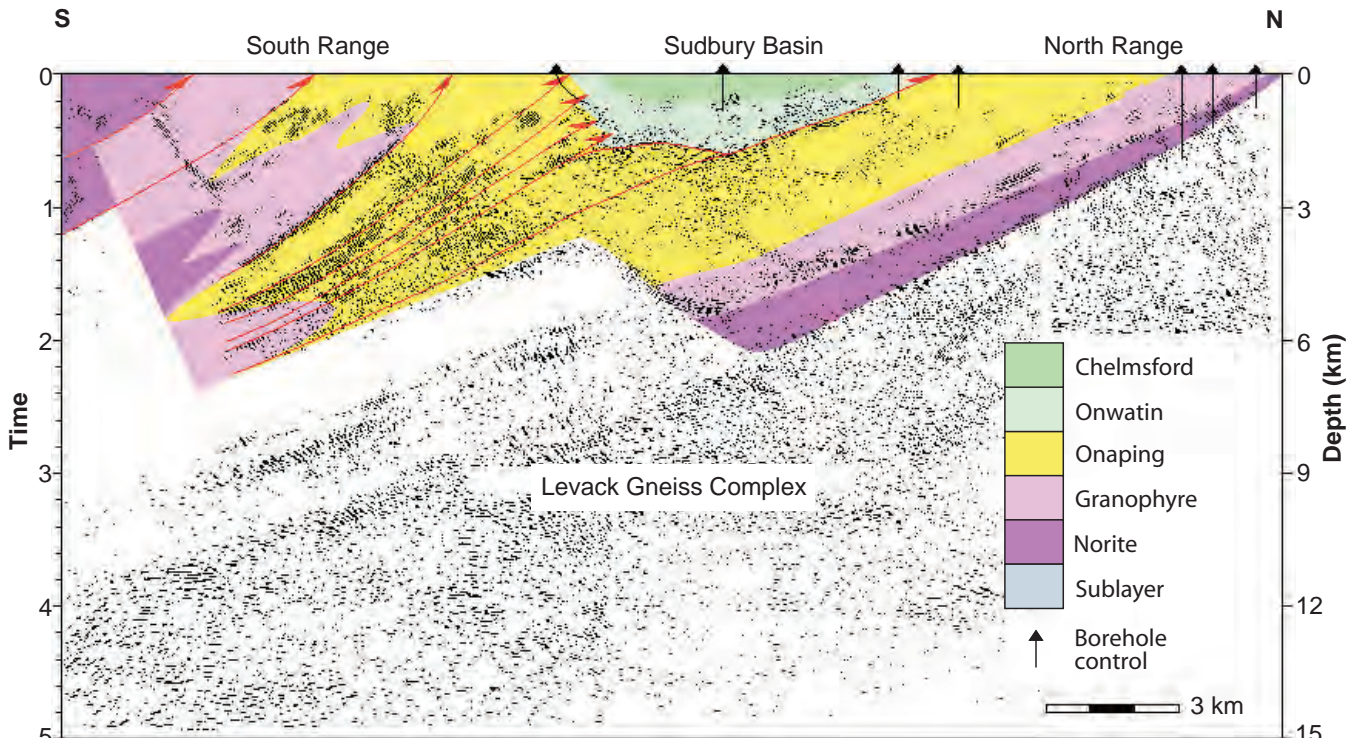


Figure 7. Lithoprobe line 41 showing reflectors associated with deep structure and lithologic contacts in the Sudbury Basin (modified from Milkereit et al., 1992). Location of seismic line 41 is shown in Figure 6.

are underlain by highly altered feeder or stringer zones and tend to be elongate and small to intermediate in size (<2 km). Although mined for Cu, Zn, and Pb, the deposits themselves are usually dominated by pyrite. As can be seen in Figure 1, massive sulphides, especially those rich in pyrite, have high acoustic impedances, making them excellent candidates for seismic exploration using high-resolution techniques. Indeed, in felsic settings, they are ideal candidates because they will be the *only* reflectors present and typically appear as P-wave, S-wave, and hybrid reflections (Bellefleur et al., 2004). Two-dimensional and VSP surveys have imaged such deposits in the Bathurst camp (Fig. 10) and the first deposit actually discovered using seismic reflection techniques was found from a 3-D exploration survey in the same camp (Fig. 11; Salisbury et al., 1997, 2003). Diffractions from massive sulphides and reflections from key stratigraphic horizons and structures have also been observed in 2-D and 3-D data from Matagami, Quebec (Adam et al., 1997, 2003; Calvert et al., 2003).

Sedimentary Exhalative Deposits

Sedimentary exhalative sulphide (SEDEX) deposits are small (<0.5 km) stratabound massive sulphide lenses formed

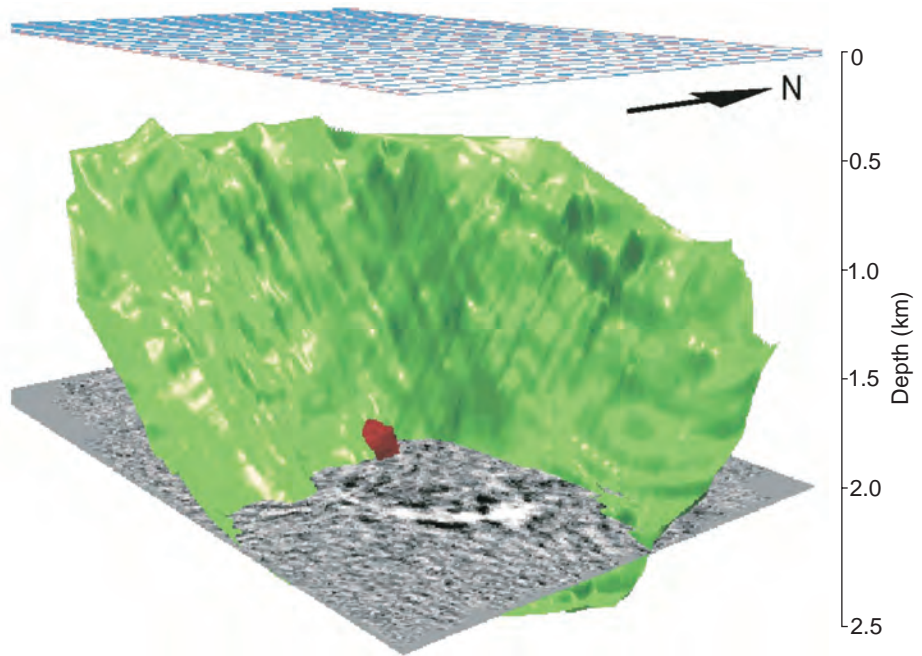


FIGURE 8. Reflection data from a 3-D cube in Sudbury showing the surface grid, horizon slice (green) corresponding to the footwall complex, and time slice at 2000 m depth. Note the bright diffraction ring in the time slice. Red spot represents known position of the Trillabelle deposit.

by submarine hydrothermal venting of brines in the cover sequence of epicontinental and intracontinental rift basins during extension. As with VMS deposits, which are closely related, SEDEX deposits are mined for Zn and Pb, but pyrite and pyrrhotite are usually the predominant sulphides (Lydon, 1995). Since these ores will have considerably higher impedances than their sediment host rocks (Fig. 1), they should make strong reflectors. Seismic reflection surveys are well suited to mapping both the sediments and the fault structures

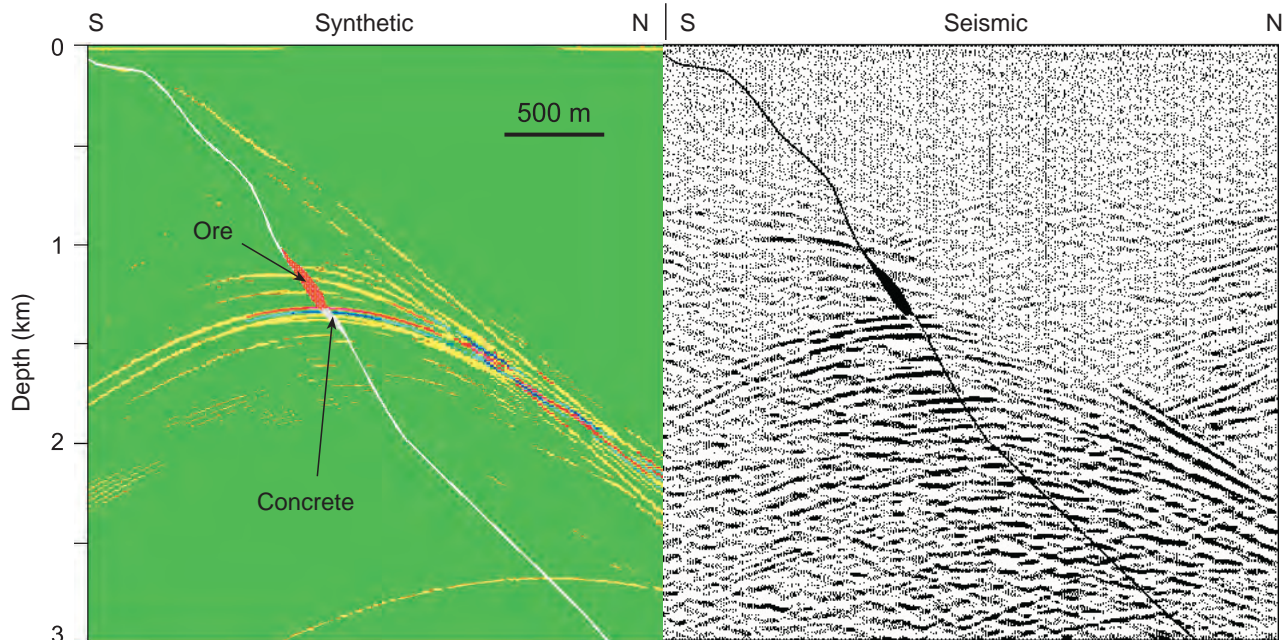


FIGURE 9. Synthetic (left) and observed (right) reflections from the massive sulphide deposit lying beneath line 43 along the footwall contact (line) near the Gertrude deposit, Sudbury Basin (G in Fig. 6). Note the diffractions at the top of the orebody, at the ore-concrete backfill contact and downdip from the deposit. Figure modified from Milkereit et al. (1996).

along which these deposits congregate, but the deposits themselves will tend to be diffractors, rather than reflectors, because of their small size. Like VMS deposits in felsic settings, SEDEX deposits should be excellent candidates for seismic exploration because they are hosted by low-impedance sediments, but modelling studies show that mafic dykes and sills in the survey area will compete for the interpreter's attention.

Mississippi Valley-Type Deposits

Mississippi Valley-Type deposits consist of swarms of small (≤ 100 m) orebodies in which Fe, Pb, and Zn sulphides fill the voids in thermokarst or solution breccias in carbonate platforms adjacent to large cratonic sedimentary basins. The deposits are typically stratiform at the district scale but individual bodies often cut vertically for short distances through the stratigraphy. These deposits will be difficult to detect and image seismically because they are small, the sulphides are diluted by breccia, and the host carbonates will have similar impedances to the ores (unless the carbonates are vuggy or the ores particularly rich in pyrite), making them acoustically transparent. Ironically, they might be detected as "white spots" in migrated high-resolution data because the breccias would show no stratigraphy, just as gas pockets obscure stratigraphy in marine sediments.

Porphyry Copper Deposits

Porphyry copper deposits are large (0.5 km across, 3 km deep) low grade deposits formed by hydrothermal activity and the crystallization of metals and volatiles from water-saturated, late-stage magmas at the roofs and peripheries of felsic to intermediate porphyritic intrusions in the root zones of andesitic volcanoes. The deposits are typically zoned both in terms of alteration and mineralization, with a potassic alteration zone characterized by biotite and K-spar near the intrusion, then a phyllic zone containing sericite and muscovite, an argillic zone containing kaolinite and clay, and an outer zone containing quartz, chlorite, and epidote further away. Copper mineralization is concentrated in the potassic and phyllic zones and is sur-

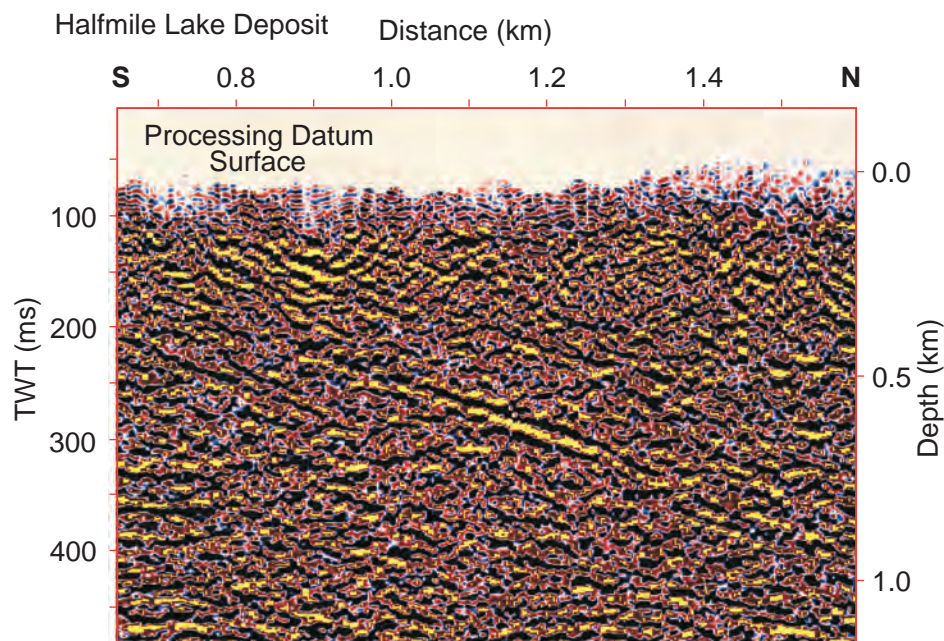


FIGURE 10. Two-dimensional multichannel seismic image of the Halfmile Lake deposit, Bathurst Camp. TWT = two-way travel time.

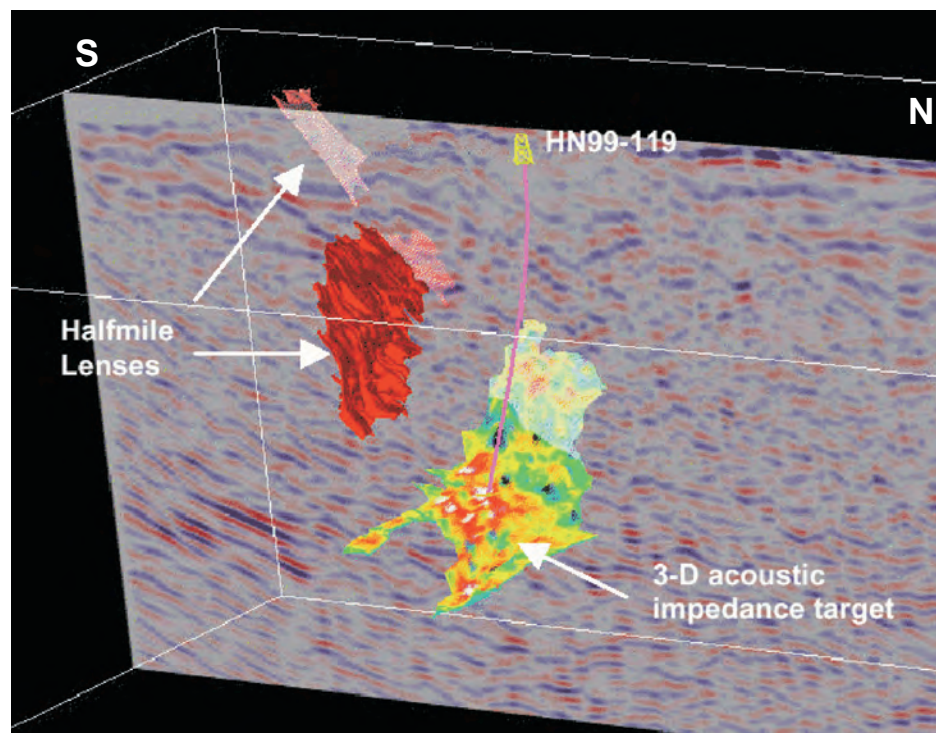


FIGURE 11. Cross-section through a 3-D seismic cube at the Halfmile Lake deposit, Bathurst Camp, showing the massive sulphide deposit discovered by seismic methods at 1300 m, plus earlier known deposits.

rounded by an extensive, diagnostic pyritic halo. Gold and silver veins are found beyond the halo.

While the ore minerals in porphyry Cu deposits have significantly higher impedances than their felsic to intermediate hosts, the deposits themselves are unlikely to be detectable using seismic reflection methods because they are low grade. Thus the surveys that have been conducted over these

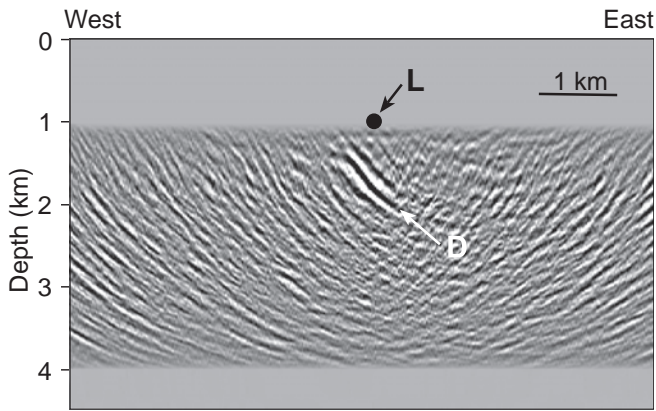


FIGURE 12. East-west section from a 3-D survey shot over the Louvicourt volcanic massive sulphide deposit, Val d'Or, Quebec. L shows the deposit location; reflection D is tentatively attributed to an alteration zone. Figure modified from Adam et al. (2004).

deposits to date have focussed on determining local and regional structure (Wright, 1981; Roy and Clowes, 2000). If the pyrite is sufficiently abundant in the pyritic haloes, however, the halo could be detected and used as an acoustic marker for the underlying Cu deposits. If the surrounding country rock is entirely felsic to intermediate, such haloes would be excellent targets because the rest of the complex would be acoustically transparent.

Unconformity Uranium Deposits

Unconformity U deposits are small ($\leq 150\text{m}$) pods and lenses of uranium oxide minerals (\pm various base metal sulphides, arsenides, and oxides) found at or near the basement unconformity in PreCambrian intracontinental sedimentary basins where the unconformity is cut by steep faults or fracture zones that focused return supergene circulation from basement, deep-seated hydrothermal fluids, or diagenetic-hydrothermal fluids from the basin fill. The unconformity is typically marked by a well developed, lateritic regolith and the deposits themselves are invariably surrounded by strong alteration haloes containing clays, chlorite, carbonates, and silica. Although high-grade uranium ores can have extremely high impedances (~ 30) because of their high densities, it is unlikely that the ore deposits themselves will be detectable using regional-scale seismic techniques because the deposits are small and the ores are generally dilute. High-resolution reflection methods can be used, however, to delineate these small tabular bodies for mining and their associated alteration haloes can likely be detected because of their low impedances and larger size. In addition, the faults associated with these deposits can be readily mapped as small basement offsets using 2- and 3-D seismic reflection techniques (Hajnal et al., 1997).

Iron Oxide Copper Gold Deposits

Iron oxide copper gold (IOCG) or Olympic Dam deposits, which are closely related to porphyry copper deposits, are small- to large-sized (< 2 km), hematite-rich bodies associated with late-stage magmas from anorogenic granites or felsic plutons in continental arcs. The hematite, which occurs together with copper sulphides, uranium oxides, and gold and constitutes 30 to 70% of the rock, is found in the matrix

of discordant felsic breccias cutting both extrusives and intrusives. Kiruna iron deposits, which occur in the same setting, are closely related to Olympic Dam deposits, but are hydrothermal in origin and occur as large (< 4 km) tabular bodies composed largely of magnetite. Although both IOCG and Kiruna deposits occur in acoustically transparent, low-impedance settings, the deposits themselves are sharply defined and dominated by hematite and magnetite, which are very high-impedance minerals, potentially making both deposit types excellent targets for seismic exploration and delineation.

Knowledge Gaps

Because seismic reflection is still an emerging technology in hardrock terranes, it has only been used on an industrial scale to delineate structure in two deposit types (stratiform gold (Pretorius et al., 2003) and magmatic PGE deposits (Duweke et al., 2002)) and it has only been extensively tested for exploration with convincing results in VMS and magmatic Ni-Cu-PGE deposits. For most other deposit types, it has only been attempted on an experimental basis, or not at all, in part because of knowledge gaps.

Acoustic Properties of Metamorphic Aureoles

While massive sulphide deposits can be detected directly because of their high acoustic impedances, many other deposit types are too diffuse to be detected seismically. Several of these deposit types, however, are typically surrounded by or closely associated with metamorphic aureoles, which might serve as proxy seismic targets. Epithermal gold and unconformity uranium deposits, for example, are invariably associated with highly altered, low-grade metamorphics, and porphyry copper deposits are commonly surrounded by distinctive, concentric alteration haloes. Similarly, the basement surrounding the feeder dykes beneath VMS deposits is commonly strongly altered. Because these aureoles are generally composed of clays and phyllosilicates, they are likely to have low acoustic impedances. While a strong reflection has been tentatively attributed to such an alteration zone near the Louvicourt deposit at Val d'Or (Fig. 12; Adam et al., 2004), since the acoustic properties of aureoles have not been studied systematically either in the laboratory or by logging in any camp, it is not known whether their internal and external boundaries are acoustically sharp, and thus detectable, or gradational.

Magnetite-Hematite Systematics

While the velocities and densities of magnetite and hematite are known, the velocity-density systematics of their host rocks and alteration products have not been examined, making it difficult to model the acoustic behaviour of typical IOCG deposits. As for metamorphic aureoles, this can be remedied by systematic laboratory and logging studies in known deposits.

Shear Wave Velocities

Compressional wave velocities and densities are known for most ores and host rocks (with the exceptions noted above), but our knowledge of shear wave velocities is much more limited, making it difficult to impossible to use the full acoustic wavefield in seismic surveys. Until this is remedied

by laboratory and logging studies, it will be difficult to move beyond the detection of orebodies and use seismic colour, amplitude versus offset (AVO) and attribute analysis for assay purposes.

Fault Zone Properties and Pathways

Since many deposit types are concentrated along fluid pathways in fault zones, it should be possible to narrow the search for ores or to search for them directly by imaging fault zones, provided the impedance contrast between the fault-zone material and the country rock, and the thickness of the fault zone itself, are sufficiently large to produce reflections. Although this could be a powerful aid to exploration, a major obstacle is that the fluid pathways in fault zones and the acoustic properties of fault-zone rocks are poorly understood because they have not been studied systematically. This could be easily remedied by conducting a series of acoustic property traverses across well known faults in major mining camps.

Properties and Geometries of Kimberlites

Finally, significant knowledge gaps exist involving the use of seismic methods to delineate kimberlite bodies. In particular, while there are strong suggestions that kimberlites should make strong reflectors, it is clear that the petrology and geometry of kimberlites is extremely variable. Systematic studies of the acoustic properties of kimberlites need to be conducted as a function of depth in order to model the seismic response of these bodies and determine the most efficient techniques for imaging them.

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